Neutrino Physics

A Coherent Path to DUNE

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Briefing to DOE OHEP

Tues 12 Jan 2021

Overview

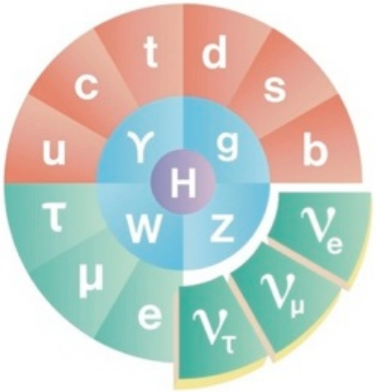
- Neutrino Physics
  - Why are Neutrinos Important? – Quantity, Ubiquity, Oddity
  - The Current, Big, Neutrino Questions
  - Addressing the Questions
  - Physics with Neutrinos from Accelerators
- Fermilab's Current and Future Neutrino Experiments
  - MicroBooNE – Matt Toups
  - ICARUS and SBND – Angela Fava
  - NOvA – Louise Suter
  - DUNE – Jen Raaf
- Neutrinos at Fermilab
  - It all leads to DUNE and Fermilab Neutrino Scientists are organized to that end
  - Fermilab Neutrino Scientists facilitate the wider neutrino community

The tiny but mighty neutrino

Neutrinos are among the most abundant particles in the universe, and among the least understood.

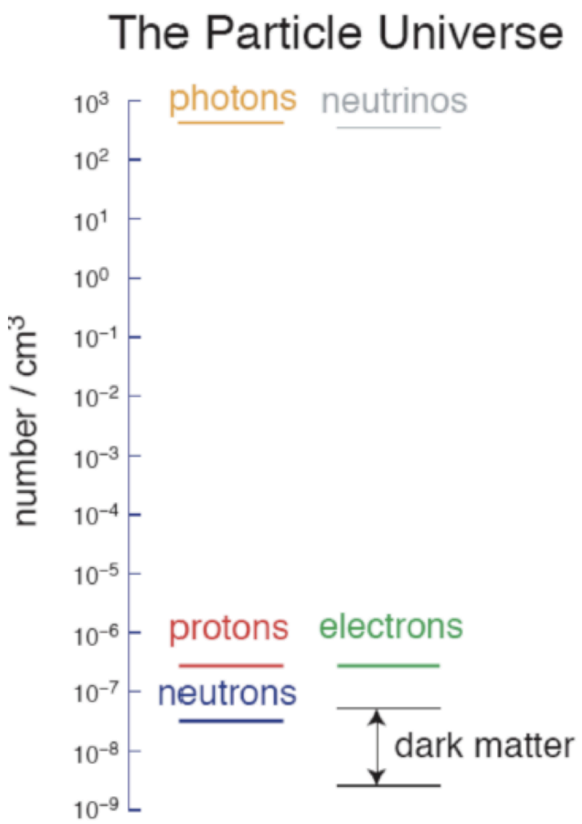
They are tiny, invisible and ghostly, passing through virtually everything and only rarely leaving a trace.

Billions of them are going through you right now and have been your whole life.

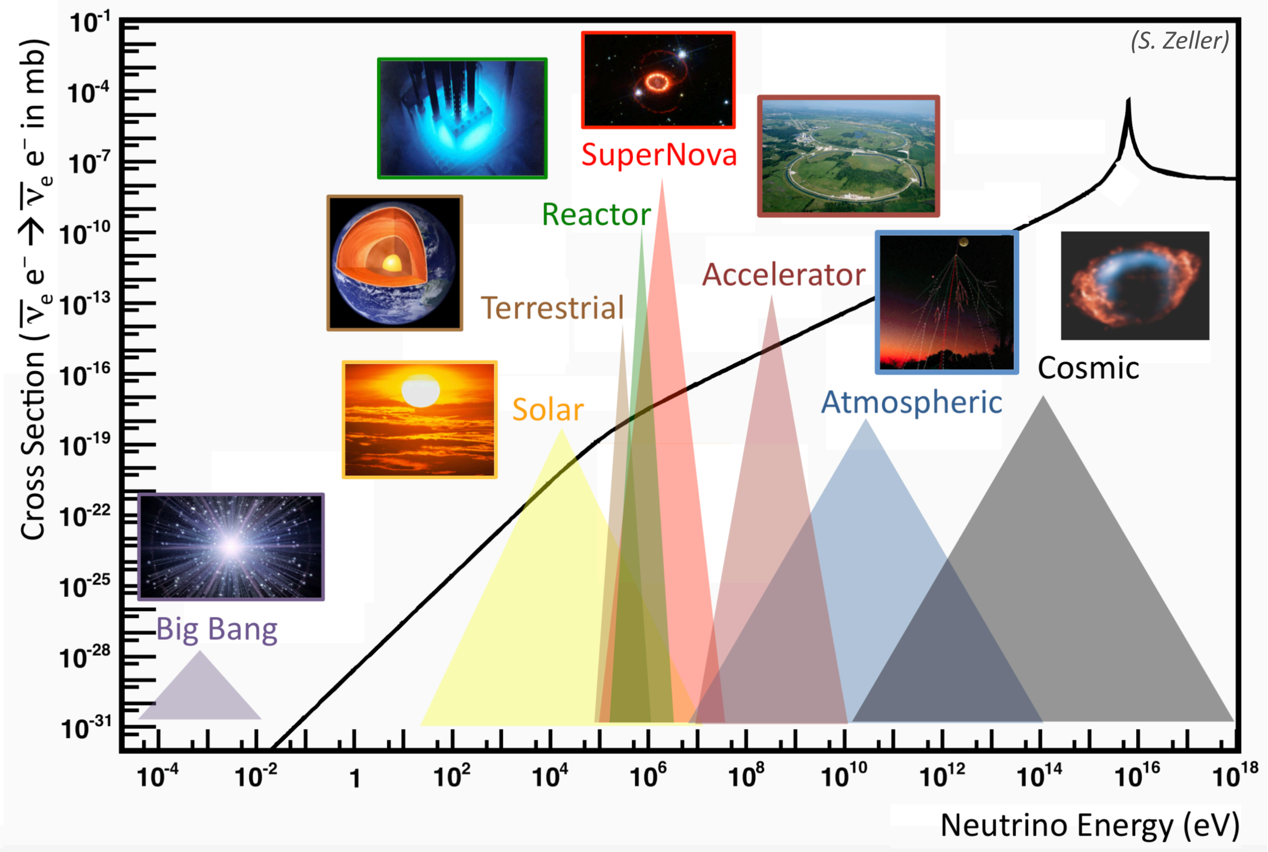


Why are Neutrinos Important? - Quantity

Neutrinos may only interact Weakly, but they are the most abundant matter particle in the universe with a pivotal role in its evolution



Why are Neutrinos Important? - Ubiquity

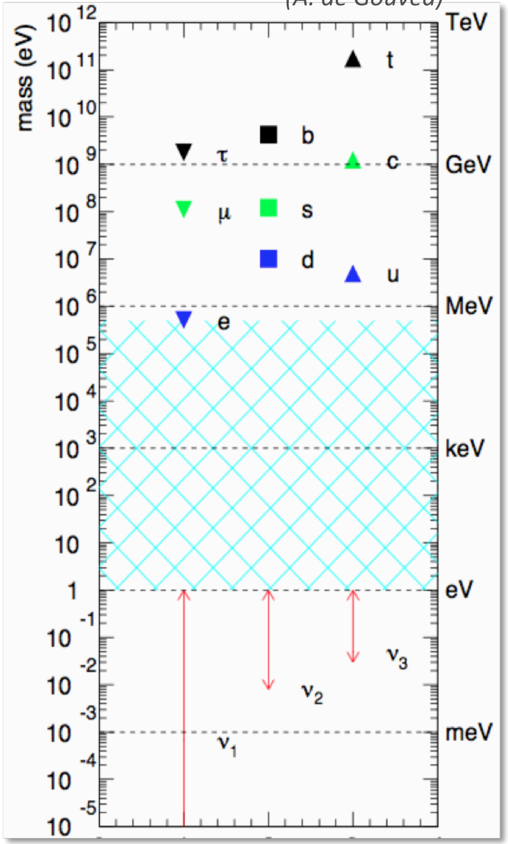


Why are Neutrinos Important? - Oddity

Neutrinos are the real oddities of the fundamental particles (only interact Weakly, ultra small, but non-zero masses). Science often advances when studying the oddities

Particle Physics has made great progress in the last half century probing the quark half of the fundamental particles. We are now in a position to propose doing similar for the neutrinos.

(A. de Gouvea)



Why are Neutrinos Important? - Oddity

The mixing between the 3 neutrino generations is starting to look very different to its quark counterpart. We don't know why but it is probably important. May hold the key to understanding why the fundamental particles exist in 3 generations

$$V_{PMNS} \approx \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

A difference between how the neutrino types mix and how the antineutrino types mix is postulated to be the reason why matter dominates over anti-matter in our universe (i.e. why we exist)

$$V_{CKM} \approx \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

The Present Neutrino Landscape

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}1&0&0\\0&\cos\theta_{23}&\sin\theta_{23}\\0&-\sin\theta_{23}&\cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13}&0&\sin\theta_{13}e^{i\delta}\\0&1&0\\-\sin\theta_{13}e^{-i\delta}&0&\cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12}&\sin\theta_{12}&0\\-\sin\theta_{12}&\cos\theta_{12}&0\\0&0&1\end{pmatrix}\begin{pmatrix}1&0&0\\0&e^{i\alpha/2}&0\\0&0&e^{i\alpha/2+i\beta}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$\Delta m_{21}^2 = 7.50\ ^{+0.22}_{-0.20} \times 10^{-5}\ \mathrm{eV}^2$

$|\Delta m_{31}^2|(\mathrm{NO}) = 2.56\ ^{+0.03}_{-0.04} \times 10^{-3}\ \mathrm{eV}^2$
$|\Delta m_{31}^2|(\mathrm{IO}) = 2.46\ ^{+0.03}_{-0.03} \times 10^{-3}\ \mathrm{eV}^2$

$m_{\mathrm{lightest}} < 0.05\ \mathrm{eV}\ (2\sigma)$

$\theta_{12} = 34.3\ ^{+1.0}_{-1.0}$ deg

$\theta_{23}(\mathrm{NO}) = 48.79\ ^{+0.93}_{-1.25}$ deg
$\theta_{23}(\mathrm{IO}) = 48.79\ ^{+1.04}_{-1.30}$ deg

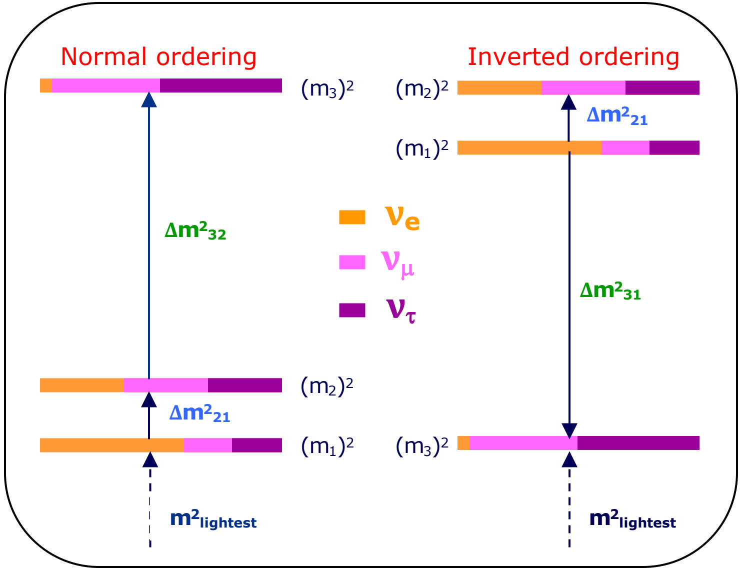
$\theta_{13}(\mathrm{NO}) = 8.58\ ^{+0.11}_{-0.15}$ deg
$\theta_{13}(\mathrm{IO}) = 8.63\ ^{+0.11}_{-0.15}$ deg

m_{lightest} = ?

Sign Δm_{32}^2 = ?

δ = ?

Adapted from P.F. de Salas et al, arXiv:2006.11237 [hep-ph] (2020)



The Current, Big, Neutrino Questions

- What are the masses of the neutrinos?
- What kind of mass do neutrinos have?
- Which neutrino is the heaviest and which is the lightest?
- Are there more than 3 kinds?
- Do neutrinos and antineutrinos oscillate in the same way (CP)?
- Is our picture correct?

We will use multiple sources of neutrinos to figure these out

Neutrino Scorecard

different neutrino sources address different questions

ν questions → / ν sources ↓	Neutrino mass	Nature of the neutrino	Mass ordering	~~CP~~	More than 3 νs?	Is our picture correct?
β decay	✔					✔
0νββ decay	✔	✔				✔
astrophysics & cosmology	✔		✔		✔	✔
atmospheric			✔			✔
reactor			✔		✔	✔
accelerator			✔	✔	✔	✔

(K. Heeger)

Neutrino Scorecard

Accelerator questions

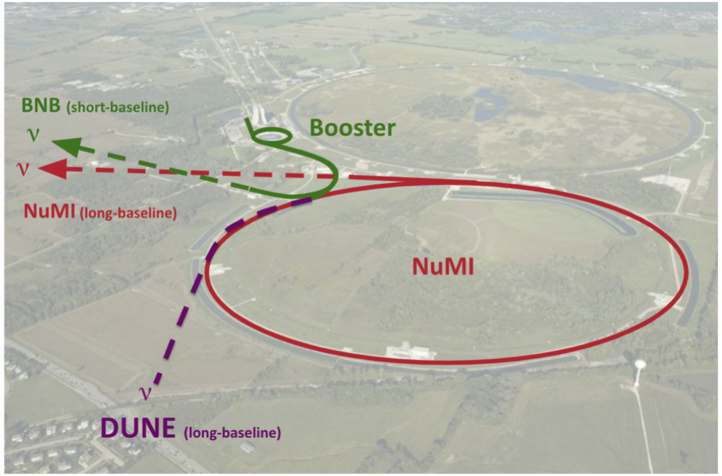
different neutrino sources address different questions

ν questions → / ν sources ↓	Neutrino mass	Nature of the neutrino	Mass ordering	~~CP~~	More than 3 νs?	Is our picture correct?
β decay	✔					✔
$0\nu\beta\beta$ decay	✔	✔				✔
astrophysics & cosmology	✔		✔		✔	✔
atmospheric			✔			✔
reactor			✔		✔	✔
accelerator			✔	✔	✔	✔

(K. Heeger)

Fermilab's Neutrino Beams

Fermilab operates the nation's largest particle accelerator complex, producing the world's most powerful low & high energy ν beams

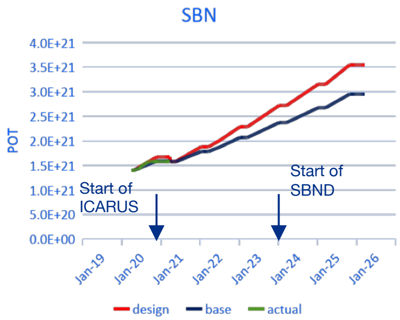


Goal is to build a world-leading ν science program anchored by LBNF/DUNE powered by MW beams from an upgraded and modernized accelerator complex

Low energy neutrino beam enables
- SBN Physics Run
- MicroBooNE physics & R&D run
- ANNIE Physics Run

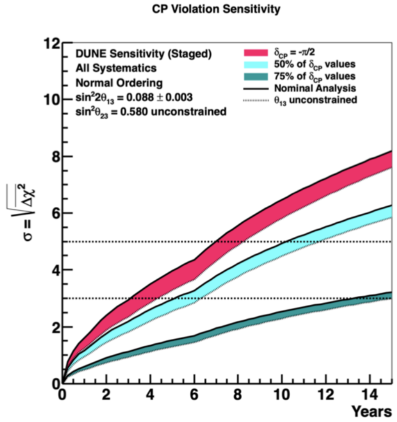
High Energy neutrino beams enable
- NOvA & DUNE programs

Essential beam upgrade programs to achieve physics programs:
- Upgrade accelerator complex and NuMI target facility to 900 kW (2021)
- PIP-II (1.2 MW)
  - CD-1 approval (2018)
  - CD-2 approval (2020)
- PIP-III (2+ MW)



(Source: M. Convery)

(Start of MicroBooNE: 2015)



(Source: DUNE TDR 2019)

Recent, Current, and Planned Fermilab Neutrino Experiments

Beamline	Experiment	Neutrino Operations Status	Main purpose(s)
NuMI	ArgoNeut	Completed 2010	ν-Ar xsecs, LAr TPC technology
	MINOS(+)	Completed 2016	Confirm atmospheric ν oscillations, measure ν mixing parameters
	MINERvA	Completed 2019	ν xsecs
	NOvA	Running	Measure ν mixing parameters, determine ν mass ordering, ν xsecs
BNB	SciBooNE	Completed 2008	ν xsecs, look for SBL ν_μ disappearance
	MiniBooNE	Completed 2012	Look for SBL ν_e appearance, ν xsecs
	MicroBooNE	Completed 2020	Study ν_e-like events, ν-Ar xsecs, LAr TPC technology
	ANNIE	Running	Neutron production in ν interactions, LAPPD technology
	SBN	Starting 2021	Look for SBL ν_e appearance, ν-Ar xsecs, LAr TPC technology
LBNF	DUNE	Seeking CD2 2021	Search for CP violation, probe 3ν mixing, supernova νs, proton decay

Neutrino Cross Section Measurements

Essential to future neutrino experiments and the neutrino community is that we **advance our knowledge of GeV scale neutrino-nucleus interactions**

Several FNAL-based experiments leading the field:

- MINERvA
- NOvA Near Detector
- MicroBooNE
- Now: ANNIE
    - measuring neutrons!
- Soon: SBND, ICARUS

Community-building activities

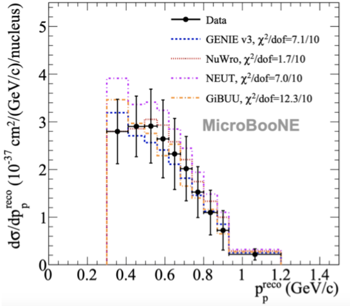
- Joint experiment-theory-computing WG
- Neutrino Theory Network
- Workshops and conferences: NuSTEC, INT, NuINT
- Programs supported by the Neutrino Physics Center (NPC):
  International Neutrino Summer School (recently 2017&2019 @FNAL),
  Workshops (11 since 2015),
  Bi-weekly neutrino seminar series since 2013,
  NPC fellowships
- Joint postdoc positions bring experts in the field to FNAL

Simulation tools and theoretical calculations

- GENIE, Geant4, Pythia, Lattice QCD

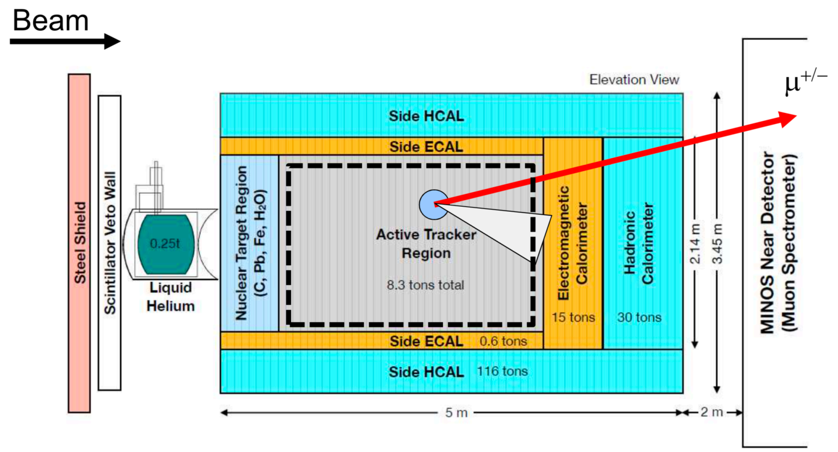
Recent results

- 5 W&C seminars in 2020
- 4 xsec publications from MicroBooNE to date
- 33 xsec publications by MINERvA to date



MicroBooNE now publishing cross section measurements of exclusive finals states (here: protons; accepted for PRD)

MINERvA

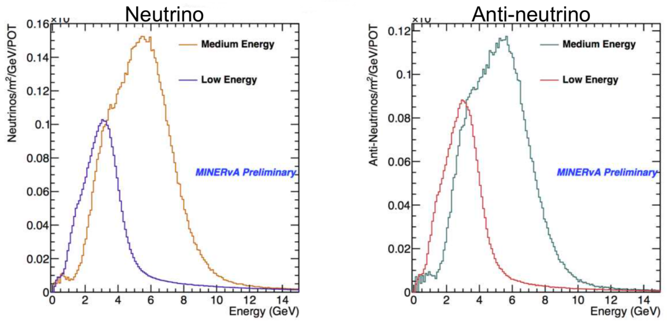


MINERvA
65 Collaborators
24 Institutions

Science Goal

- Measurement of neutrino cross sections
  - ν_μ and $\overline{\nu_\mu}$, different interaction channels low and medium energy beam configurations
  - Different nuclear targets above and below Ar
  - Developing flux constraint technique for DUNE

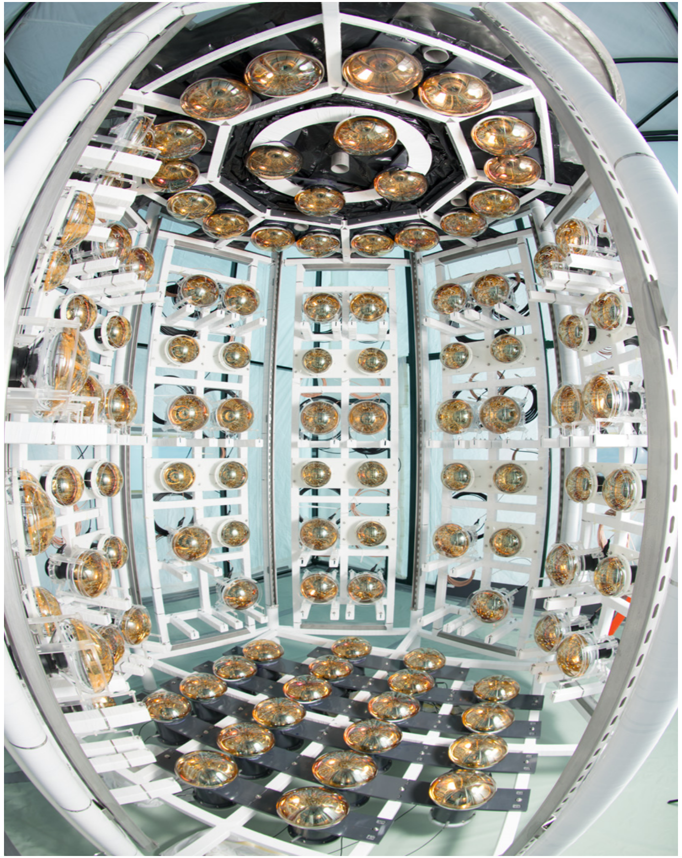
  All are essential inputs for oscillation experiments



- 8 tons active scintillator target
- Passive targets: Carbon, Lead, Iron (solid), water (liquid), cryogenic Helium
- Surrounded by electromagnetic and hadronic calorimeters
- MINOS near detector used as muon spectrometer
- Took data from 2010 to 2019

ANNIE

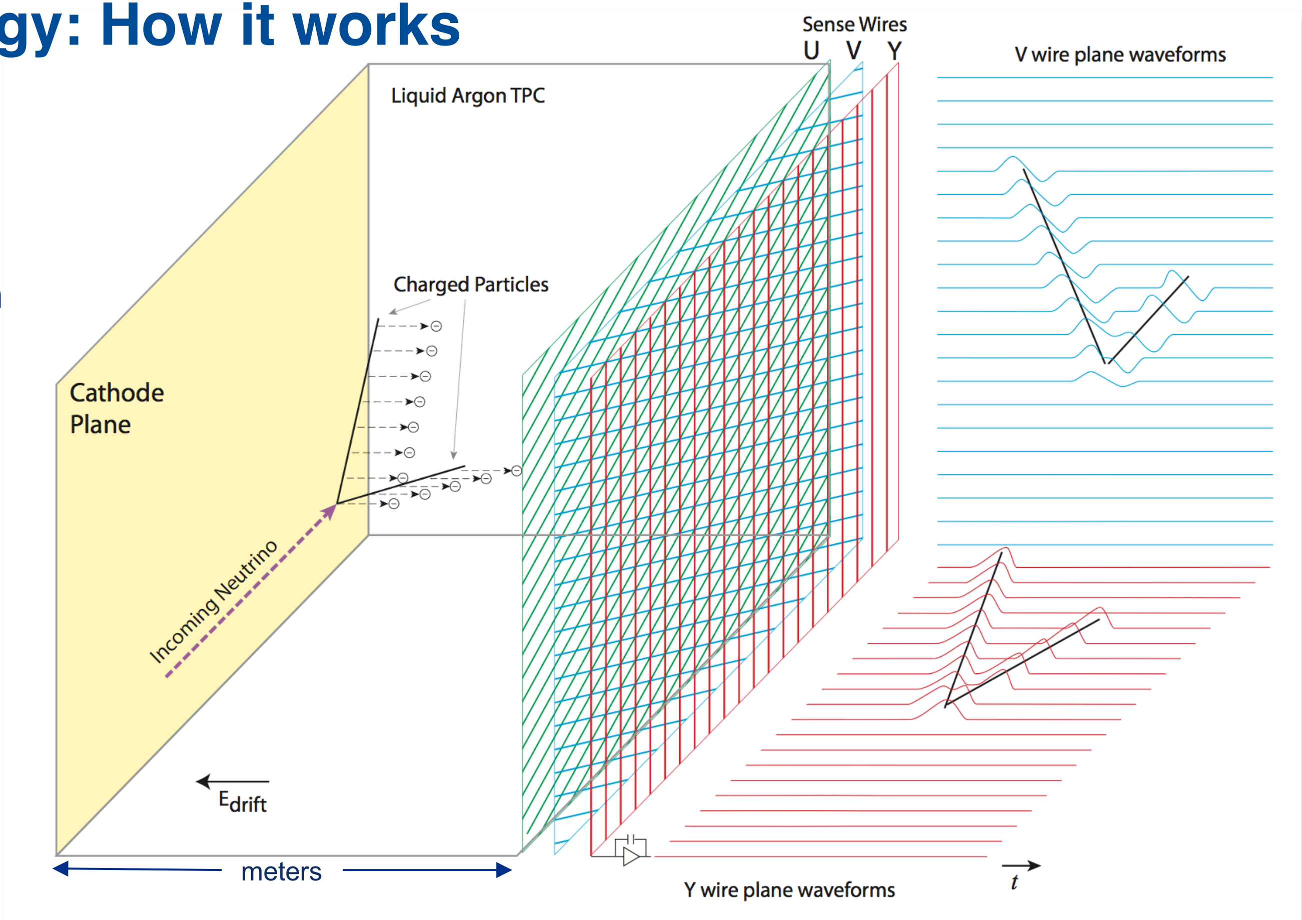
- The Accelerator Neutrino Neutron Interaction Experiment (ANNIE) is a 26-ton gadolinium-doped water Cherenkov detector instrumented with both
  - conventional photomultiplier tubes (PMTs) and
  - Large Area Picosecond Photodetectors (LAPPDs).
- Located in the Booster Neutrino Beam (BNB)
- ANNIE has two goals:
  - perform a measurement of the production of neutrons from ν_μ interactions as a function of Q2 to constrain neutrino-nucleus interaction models
  - demonstrate the power of new fast-timing, position-sensitive detectors by making the first deployment of LAPPDs in a physics experiment.
- Data already taken without Gd in main detector and without LAPPDs
- FY21 run will have Gd in the main detector and a small number of LAPPDs



LAr TPC Technology: How it works

Goal:
- Instrument 100s to 1000s tons of target material with mm resolution

Need:
- liquid argon = ν target
- cathode
- anode, wire planes
- high voltage (10’s of kV)
- good argon purity (ppt)



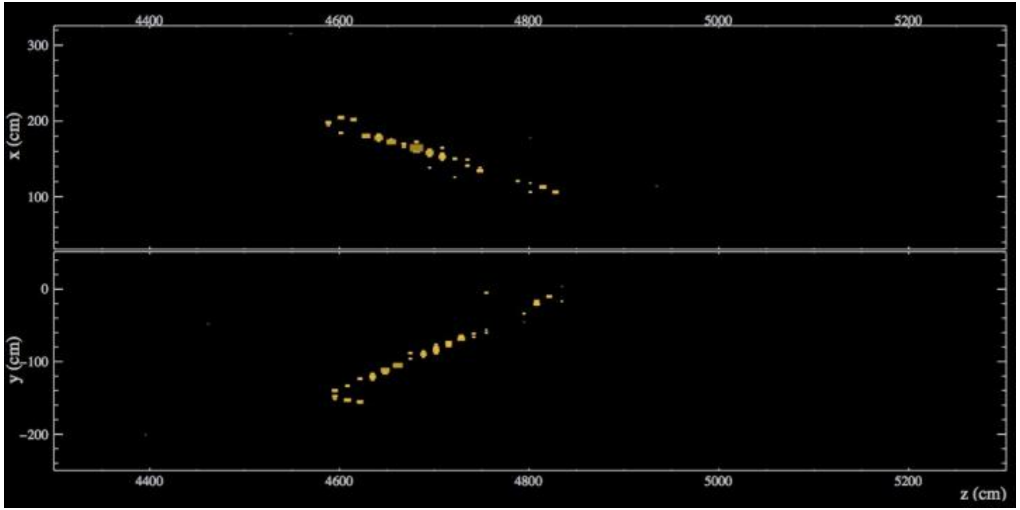
LAr TPC Technology

LAr TPC technology has finer resolution than earlier ways of instrumenting ktons of mass

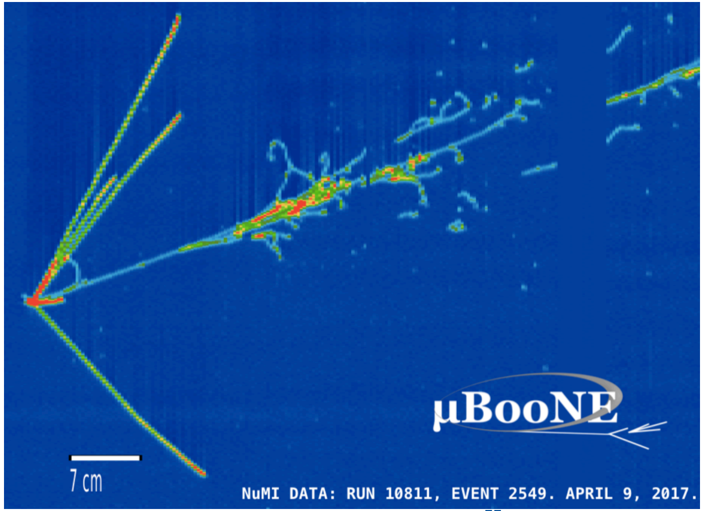
This gives greater efficiency to tell signal events (especially those caused by electron neutrinos) from background events

- Translates into a reduction in the necessary size of detectors
- The better resolution also facilitates a broader physics program

~GeV ν_e candidate event in the NOvA detector



~GeV ν_e candidate event in the MicroBooNE detector



Liquid Argon R&D

- Fermilab hosts multiple test facilities within its Nobel Liquid Detector Development Facility and test beam facility which are all available for community use.
- Developing the expertise and knowledge to enable the success of DUNE
  - High voltage, Argon purity, Cold electronics testing, Photon detector testing, and TPC design and readout testing

Liquid Argon R&D Facilities

- TallBo (470 liters)
  - Light Detection, electronics and small TPCs
- Blanche (550 liters)
  - High voltage tests
- Materials Test Stand (250 liters)
  - Cold electronics and materials testing
- Liquid Argon Purity Demonstrator (30-ton)
  - Purity, large-scale long-duration tests
- 35-ton cryostat
  - DUNE APA test, purity, High Voltage tests
- ICEBERG (4.2 tons)
  - DUNE cold electronics and light collection testing
- Test Beam
  - TPC and readout in a hadron beam

Blanche - **Lockwitz**

Liquid Argon Purity Demonstrator

Tallbo - ANL RA

Materials Test Stand

Collaborations using LAr R&D facilities

Fermilab LAr R&D facilities used by collaborators from 50 labs and institutions

Penn University of Pennsylvania
University of Cincinnati
University of Maryland 1856
Science & Technology Facilities Council Rutherford Appleton Laboratory
University of Oxford
SLAC National Accelerator Laboratory
NIST Center for Neutron Research
The University of Alabama
Berkeley Lab
Stony Brook University
South Dakota School of Mines & Technology
CERN
UFG
u^b Universität Bern
Duke University
William & Mary Chartered 1693
UCLA
Lancaster University
Brookhaven National Laboratory
Unicamp
University of Sussex
Warwick The University of Warwick
Wisconsin University of Wisconsin-Madison
UC Davis
Massachusetts Institute of Technology
Manchester 1824 The University of Manchester
The University Of Sheffield.
National Centre for Nuclear Research Świerk
University of Hawai'i
Michigan State University
Colorado State University
Kansas State University
INFN Istituto Nazionale di Fisica Nucleare
University of Texas Arlington
Universidade Federal do ABC
UMD Duluth
The University of Chicago
Argonne National Laboratory
Unifal MG Universidade Federal de Alfenas
Yale
UCL
Texas The University of Texas at Austin
LSU Louisiana State University
KEK
Boston University

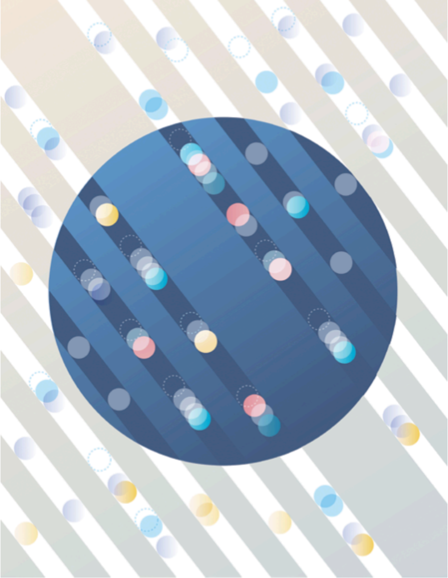
Fermilab Neutrino Program: Defined by and aligned with the P5 Plan

Recommendation 12: In collaboration with international partners, develop a coherent short- and long-baseline neutrino program hosted at Fermilab.

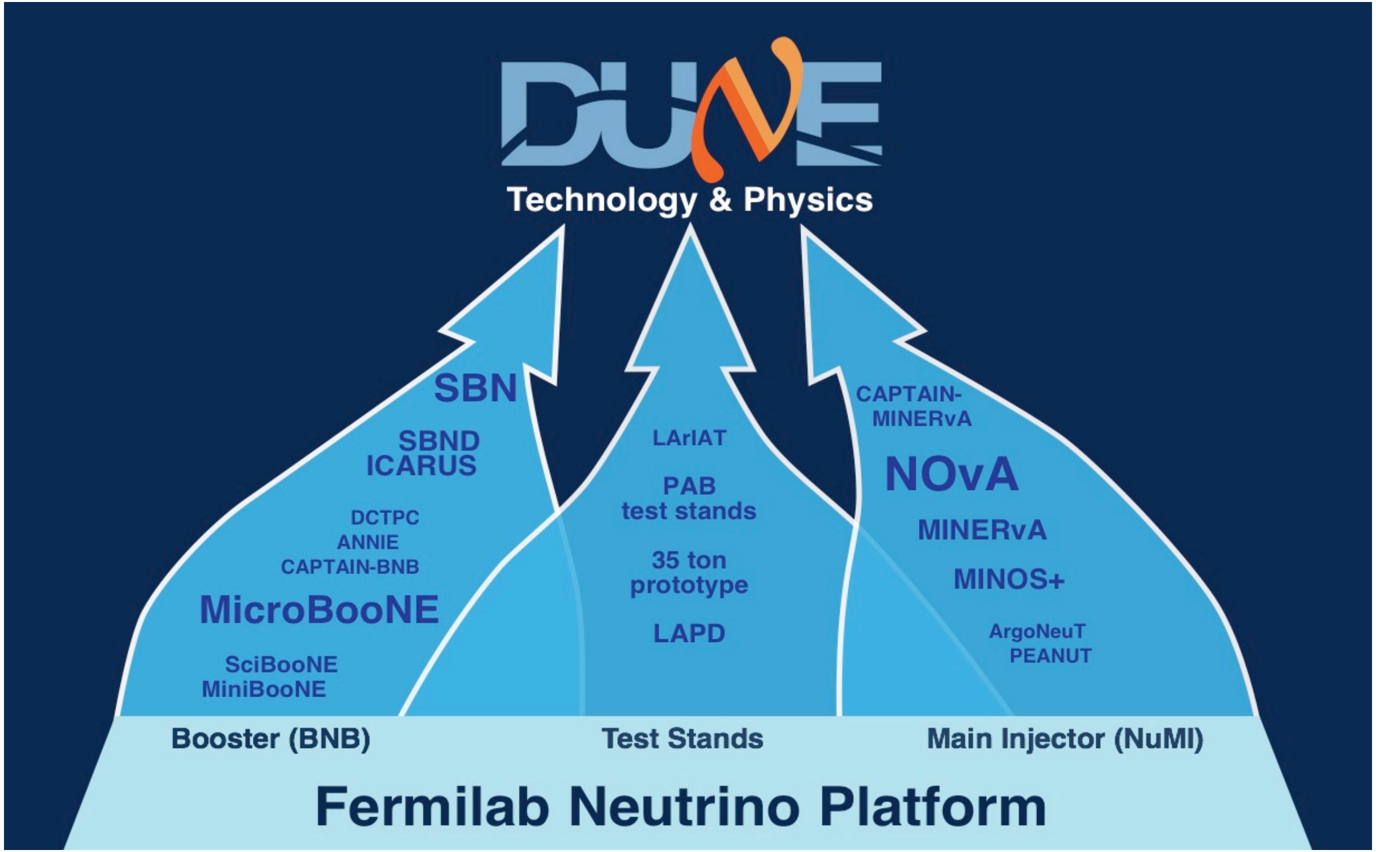
Recommendation 13: Form a new international collaboration to design and execute a highly capable Long-Baseline Neutrino Facility (LBNF) hosted by the U.S. To proceed, a project plan and identified resources must exist to meet the minimum requirements in the text. LBNF is the highest-priority large project in its timeframe.

Recommendation 15: Select and perform in the short term a set of small-scale short-baseline experiments that can conclusively address experimental hints of physics beyond the three-neutrino paradigm. Some of these experiments should use liquid argon to advance the technology and build the international community for LBNF at Fermilab.

Pursue the physics associated with neutrino mass



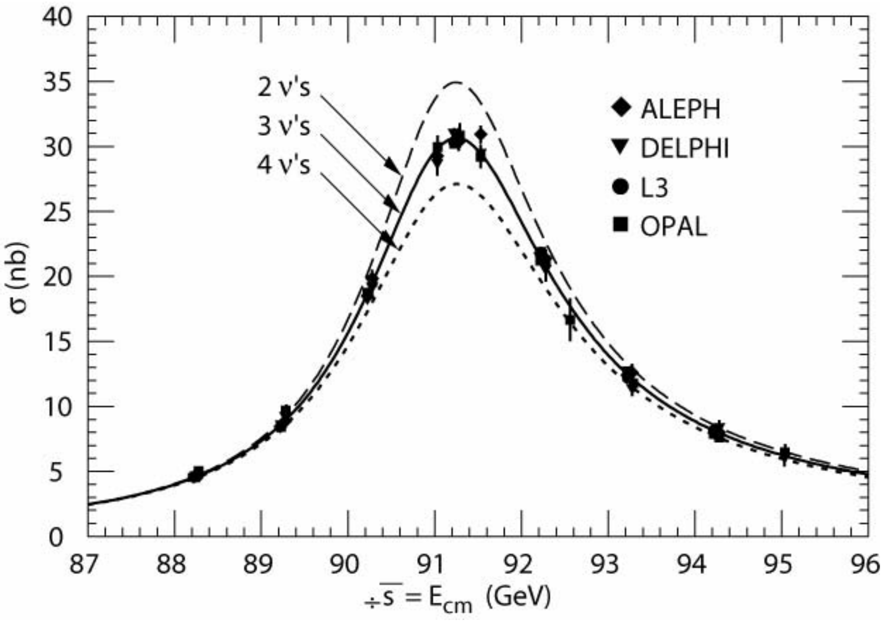
All roads lead to DUNE



Extra Slides

Three Active Neutrino Species

- Only 3 light, Weakly interacting neutrinos (LEP Z width)
- Oscillations with Δm^2_{solar} and Δm^2_{atm} are well established
- Therefore a 4th light state must be sterile



What are the Masses of the Neutrinos?

Tightest constraints come from analysis of cosmological data, measures Σm_ν

Can measure m_β (a weighted sum of m_ν) by carefully measuring the shape of a β decay spectrum near endpoint - KATRIN result $m_\beta < 1.1$ eV (90% CL)

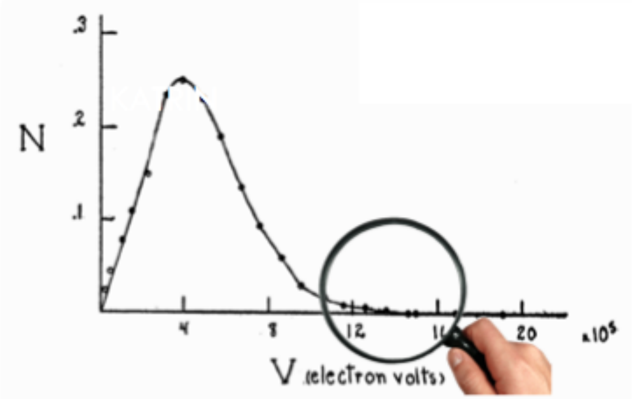
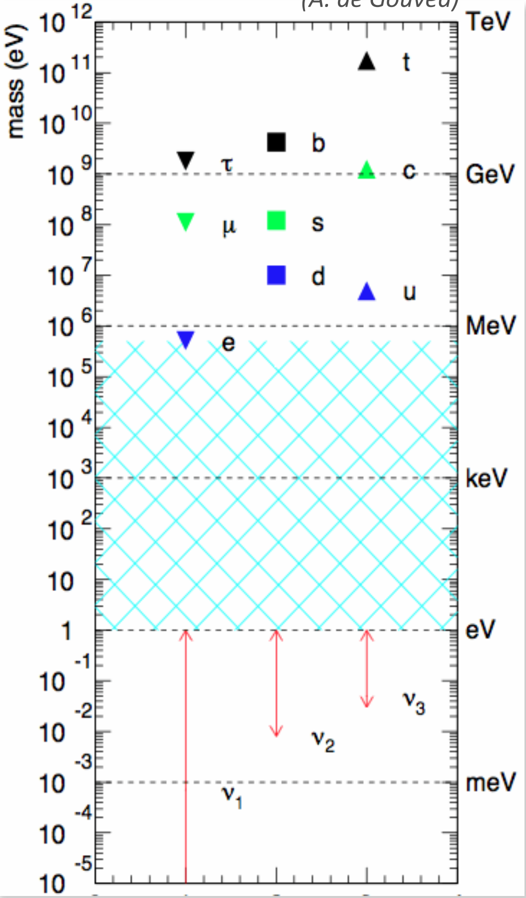


FIG. 5. Energy distribution curve of the beta-rays.

$$^3\mathrm{H} \rightarrow {}^3\mathrm{He}^+ + e^- + \bar{\nu}_e$$

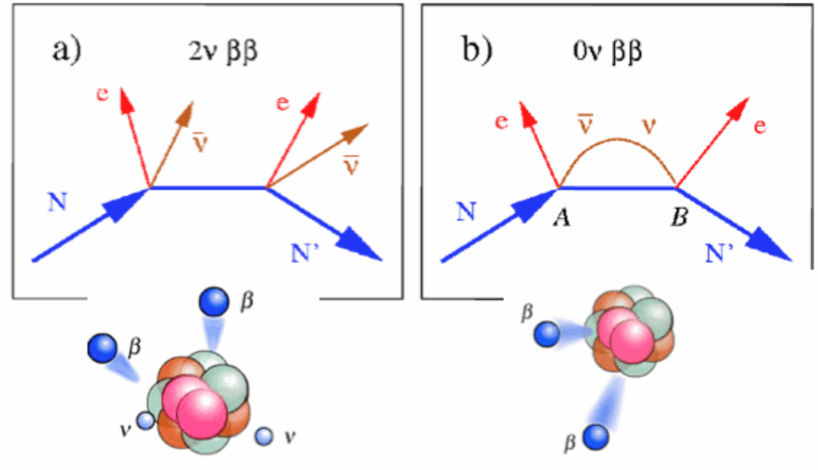
(A. de Gouvea)

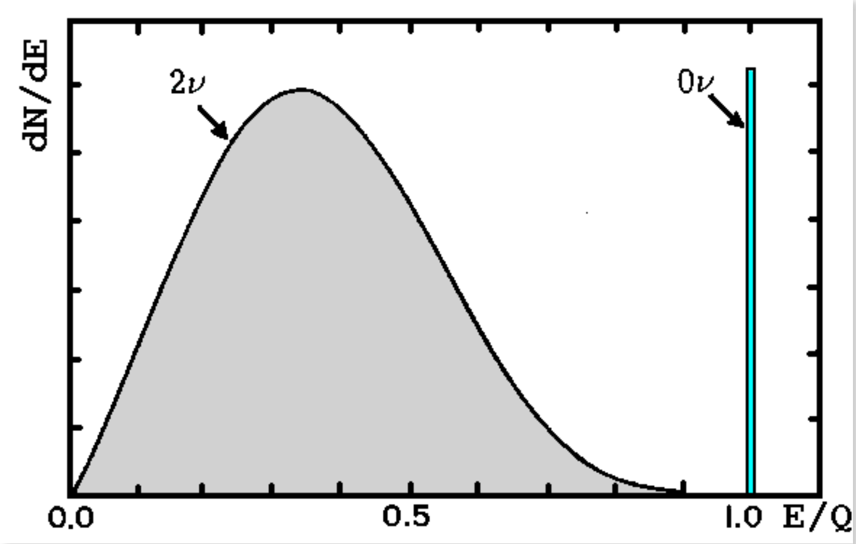


What Kind of Mass do Neutrinos have?

Are neutrinos Dirac or Majorana particles?

Since the neutrino has no electric charge, it can be it's own antiparticle ($\nu = \bar{\nu}$) → Majorana





If νs are Majorana particles ($\nu = \bar{\nu}$) then it allows this special process (0νββ)

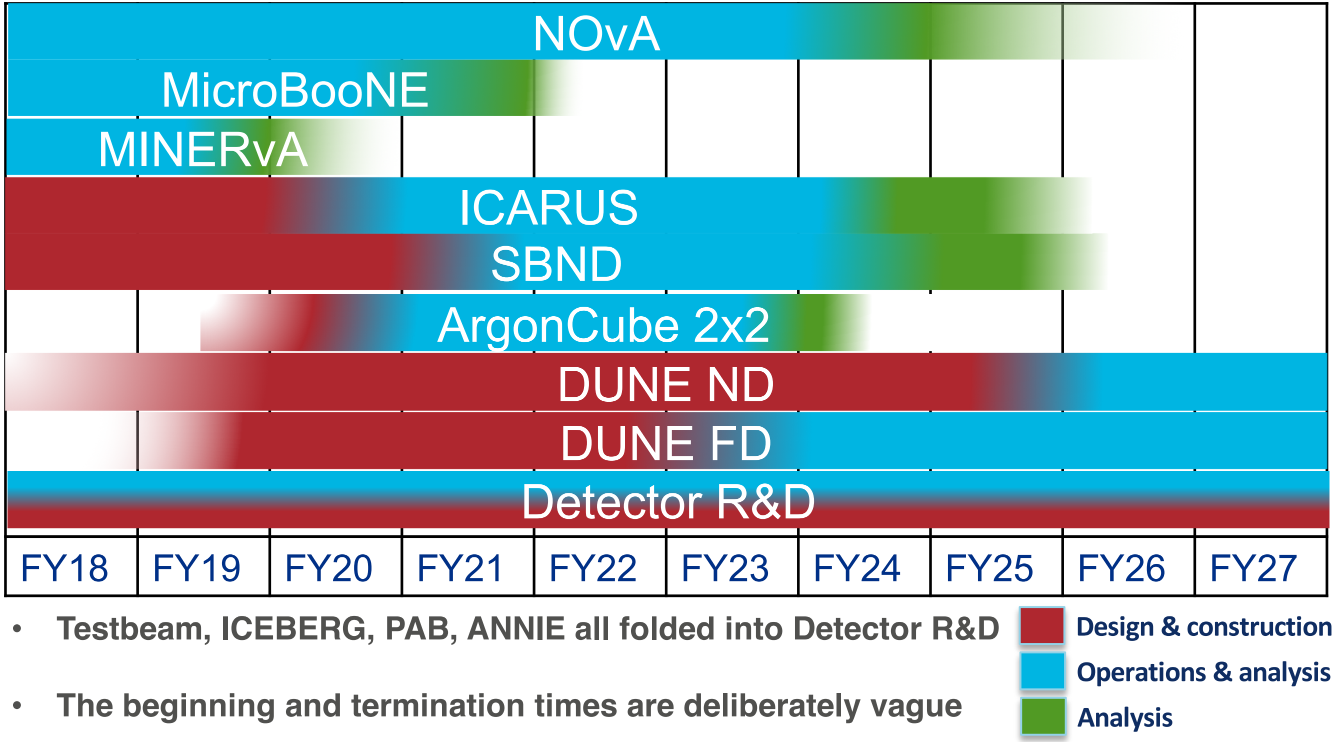
Accelerator Neutrinos: More than Three Neutrinos? Is our Picture Correct?

- Several Neutrino experiments have measured count rates of different neutrino flavors that cannot be accounted for by the 3ν mixing scheme
  - LSND anomalous rate of anti-electron neutrino events
  - MiniBooNE low energy excess of electron neutrino and anti-electron neutrino candidate events
  - Reactor neutrino experiments see fewer anti-electron neutrinos than expected
  - Gallium solar neutrino experiments saw fewer electron-neutrino calibration events than expected

- May be new physics, may be sterile neutrino state at ~1eV, may be unexpected backgrounds, may be inadequate understanding of neutrino source,…..

- …..but warrants further study….

Rough Neutrino Experiment Timeline



- **Testbeam, ICEBERG, PAB, ANNIE all folded into Detector R&D**
- **The beginning and termination times are deliberately vague**
- **It all culminates in DUNE**

Accelerator Neutrinos:
Mass Ordering, CP Violation, Is our Picture Correct?

- Carefully study electron neutrino appearance from accelerator produced muon neutrinos and compare to the anti-neutrino case

- Need to have an L and E such that interference between solar and atmospheric scales can be seen

$$P(\nu_\mu \to \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}\mp aL)}{(\Delta_{31}\mp aL)^2}\Delta_{31}{}^2$$
$$+\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}{}^2$$
$$+\cos\delta\sin 2\theta_{23}\sin 2\theta_{12}\sin 2\theta_{13}\cos\Delta_{32}\left(\frac{\sin(\Delta_{31}\mp aL)}{(\Delta_{31}\mp aL)}\Delta_{31}\right)\left(\frac{\sin(aL)}{(aL)}\Delta_{21}\right)$$
$$+\sin\delta\sin 2\theta_{23}\sin 2\theta_{12}\sin 2\theta_{13}\sin\Delta_{32}\left(\frac{\sin(\Delta_{31}\mp aL)}{(\Delta_{31}\mp aL)}\Delta_{31}\right)\left(\frac{\sin(aL)}{(aL)}\Delta_{21}\right)$$

$$P(\bar{\nu}_\mu \to \bar{\nu}_e): \quad \sin\delta \to -\sin\delta, \quad a \to -a$$

Matter effect: $a \equiv G_F N_e/\sqrt{2} \approx (4000\text{ km})^{-1}$

$$\Delta_{ij} \equiv 1.27\Delta m^2{}_{ij} L/E$$

L(km), E(GeV), m(eV)

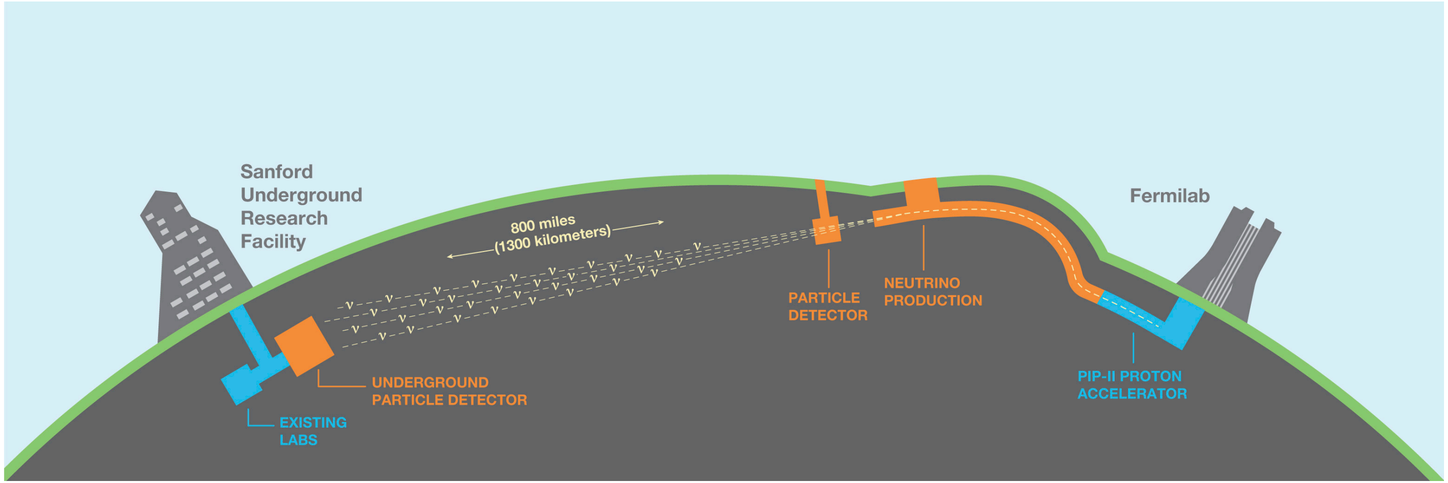
The NOvA Experiment

The NOvA Experiment

- Long-baseline neutrino oscillation experiment
- NuMI beam: ν_μ or $\bar{\nu}_\mu$
- 2 functionally identical, tracking calorimeter detectors
  - Near: 300 T underground
  - Far: 14 kT on the surface
  - Placed off-axis to produce a narrow-band spectrum
- 810 km baseline
  - Longest baseline of current experiments.

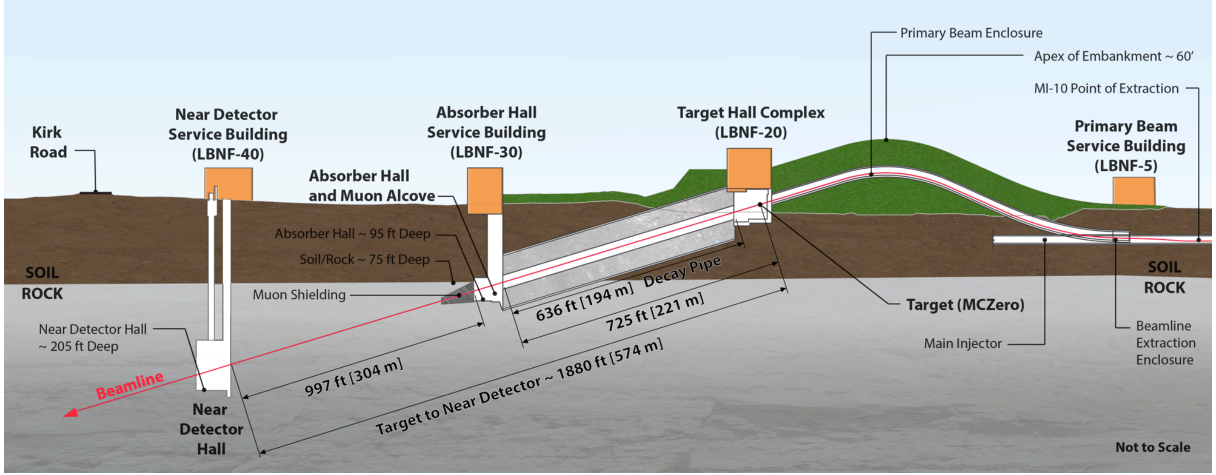
The DUNE Experiment

*"The minimum requirements to proceed are the identified capability to reach an exposure of at least **120 kt·MW·year** by the **2035** time frame, the far detector **situated underground** with cavern space for expansion to at least 40 kt **LAr** fiducial volume, and **1.2 MW beam power** upgradeable to multi-megawatt power. The experiment should have the demonstrated capability to search for **supernova neutrino (SN) bursts** and for **proton decay**, providing a significant improvement in discovery sensitivity over current searches for the proton lifetime."* **P5 Report**



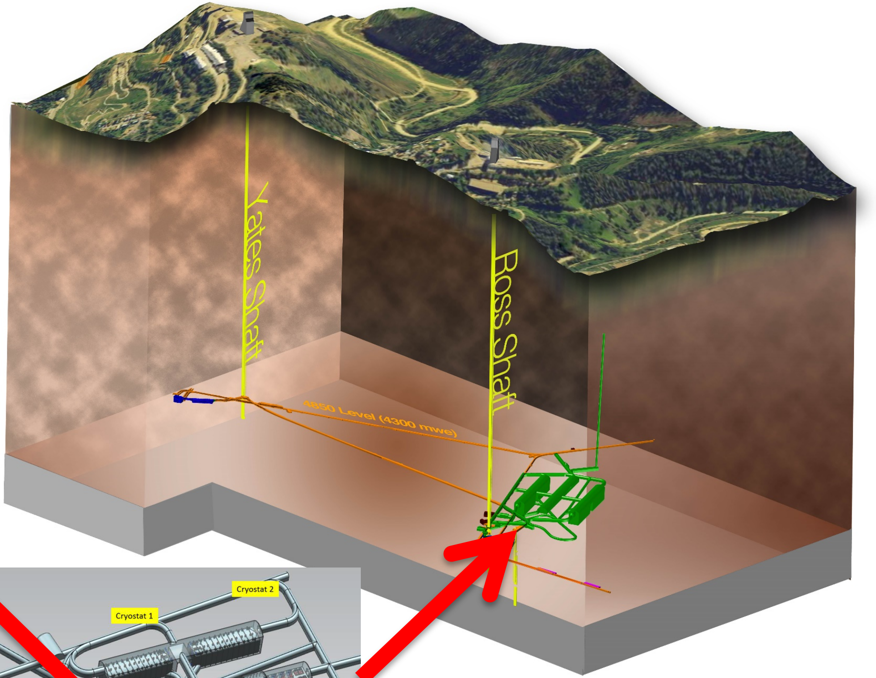
LBNF/DUNE Near Site at Fermilab, Batavia, IL

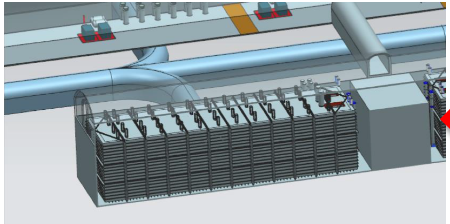
- Primary proton beam @ 60-120GeV extracted from Main Injector
- Initial 1.2 MW beam power, upgradable to 2.4 MW
- Embankment allows target complex to be at grade and neutrino beam to be aimed to Lead, SD
- Decay region followed by absorber
- Four surface support buildings
- Near Detector facility



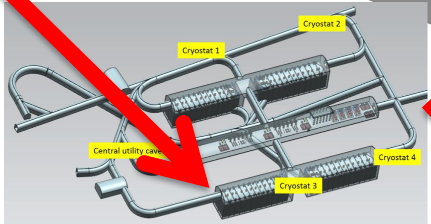
LBNF/DUNE Far Site at Sanford Underground Research Facility, Lead, SD

- Staged Approach to 40kt (fiducial)
- Flexibility for staging & evolution of LAr TPC technology design
- Assume the four 10kt liquid Argon TPCs will be similar but not identical





Assume four identical cryostats
15.1 (W) x 14.0 (H) x 62 (L) m^3



Four chambers hosting four independent 10kt FD modules

The Short Baseline Neutrino (SBN) Program

Detector	Distance from BNB Target	Active LAr Mass
SBND	110 m	112 ton
MicroBooNE	470 m	87 ton
ICARUS	600 m	476 ton